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MATERIAL LABORATORY

NEW YORK NAVAL SHIPYARD
BROOKLYN 1, N. Y.

TECHNICAL REPORT

S E C U R I T Y   I N F O R M A T I O N

THERMAL RADIATION STUDIES
REPORT OF PROGRESS, OCTOBER-DECEMBER, 1952

T.I. Monahan

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S E C U R I T Y   I N F O R M A T I O N

Lab. Projects 5046-2, 5046-3

Progress Report 8

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INTRODUCTION

Reported herein is the progress of the Naval Material Laboratory in its Thermal Radiation Studies sponsored by the Armed Forces Special Weapons Project, including the Laboratory's participation in the field tests.

GENERAL PROGRESS

A major effort of the Naval Material Laboratory in its Thermal Radiation studies during the current quarter included experimental work in preparation for the Laboratory's prosecution of Project 8.9, Operation KNOTHOLE and calibration work for other agencies engaged in this Operation, including the Bureau of Aeronautics, Naval Air Material Center, Strategic Air Command, Army Chemical Center, Wright Air Development Center and the University of Dayton as a subcontractor to WADC. As a result of this work, the laboratory program has lagged. The development of a skin simulant was emphasized, with particular attention given to obtaining fundamental data which will be of value in correlating exposures with the physical backing with actual animal exposures.

Detailed progress on each of the several problems under investigation follows.

REPORTS OF TECHNICAL PROGRESS-PARTICIPATION IN FIELD TESTS

1. CORRELATION OF LABORATORY AND FIELD DAMAGE (Operation GREENHOUSE).

It is expected that the Naval Material Laboratory report covering its participation in Operation GREENHOUSE will be published during the next quarter. A summary of the significant findings of the NML Greenhouse studies was included in the June 1952 Quarterly Progress Report.

2. ATMOSPHERIC TRANSMISSION AND WEATHER MEASUREMENTS (Operation TUMBLER-SNAPPER).

During the current quarter the final draft of the NML Project 8.4 report was forwarded to the Armed Forces Special Weapons Project. The findings of this experiment are summarized in the June, 1952 Progress Report.

3. THERMAL RADIATION MEASUREMENTS, USING PASSIVE INDICATORS (Operation TUMBLER-SNAPPER).

During the current quarter the final draft of the NML Project 8.4 report was forwarded to the Armed Forces Special Weapons Project. The significant findings are summarized in the June 1952 Progress Report.

4. EFFECTS OF THERMAL RADIATION ON MATERIALS (Operation KNOTHOLE).

The scope of the NML studies at Operation KNOTHOLE has been determined from the requirements of the laboratory studies and the knowledge gained during previous field tests. The NML experiment, as originally proposed, may be divided into four subjects:

a. Source spectrum
b. Variation of thermal damage to materials as a function of time of exposure.
c. Transfer of heat through clothing.
d. Protective value of materials.

The equivalent black-body temperature of the total thermal radiation causing damage to materials will be determined by means of passive indicators (metal foils) and appropriate filters. The information to be gained is of value in determining the effect of source temperature on thermal damage to materials. Foils are employed because, like most materials, their response to the "tail" energy of the field pulse should be negligible . These measurements will be made at several stations corresponding to radiant exposures of 5 to 25 cal/cm^2.

The influence of the "tail" energy in the field pulse will be studied through the exposure of representative materials to the thermal radiation for a series of discrete times ranging from 50 milliseconds up to the total time of the pulse. This is accomplished by means of a sliding shutter actuated by the initial flash. The data obtained in Operation BUSTER gave a reliable indication of the shape of the field pulse, but were not adequate to indicate the effect of the "tail" energy on thermal damage to materials. Measurements will be made at radiant exposure levels ranging from 12 to 25 cal/cm^2.

The principal purpose of the NML participation in Operation KNOTHOLE is the evaluation of the proposed skin simulant under field conditions to determine whether exposures to a laboratory source of thermal radiation properly indicate the behavior of a cloth assembly under exposure to the thermal radiation of an atomic explosion. The temperature-time history of the backing behind various cloth assemblies will be determined for several geometries of exposure. Since the ideal skin simulant also includes a means of measuring the amount of heat incident on and absorbed by the backing, several passive indicators including paints, waxes, and papers, will be evaluated. If the instrumentation is proven reliable, the data will indicate the amount of heat transferred by a cloth assembly.

The protective value of cloths has been determined empirically in the laboratory and the relationships obtained will be proven under field conditions.

During the current period the experimental planning has advanced and the necessary instrumentation and fabrication of exposure assemblies have been initiated.

5. THERMAL RADIATION MEASUREMENTS, USING PASSIVE INDICATORS (Operation KNOTHOLE).

The Naval Material Laboratory was requested by several Armed Services agencies to furnish technical assistance in the way of selecting, procuring, calibrating and evaluating passive indicators for use in connection with the participation of these agencies in Operation KNOTHOLE. This work is summarized herein.

The primary instrumentation, to be employed by the Army Chemical Center in determining the protection against thermal radiation afforded by smoke clouds, includes papers and cloths. These passive indicators have a range of sensitivities to cover the possible values of radiant exposure, 0.9 to 21 cal/cm^2. The indicators are to be mounted on semi-circular roundels; they will be mounted at each point of measurement to cover 360° in each of three mutually perpendicular planes. The indicators have been calibrated through exposure to the laboratory carbon-arc source; this calibration will be checked by exposing the materials at several stations in the clear area. NML will measure the spectral distribution of the energy received at three stations in the smoke area, and will evaluate the exposures at the time of test.

The Naval Air Experimental Station requested assistance on the selection and calibration of passive indicators for use in determining the radiation incident on the outer skin of aircraft which will orbit about one of the explosions. Eight cloths having a range of 8 to 30 cal/cm^2 were selected and calibrated with an aluminum backing. Calibration charts and instructions for evaluating field data were given NAES personnel.

Eleven doped-fabric systems have been evaluated for the Wright Air Development Center in order to determine which is most heat-resistant and, therefore, desirable for use on the aircraft which will be exposed at the tests for data on the effects of blast. Similar data were obtained for the Strategic Air Command, Omaha, Nebraska, in connection with an identical problem. These data will be published in an NML project report at a later date.

The University of Dayton, acting as a sub-contractor to the Wright Air Development Center, has requested the NML to calibrate its temperature-sensitive-coated papers under conditions prevalent in the field, that is, mounted on the reverse side of an irradiated aluminum strip. This work will be completed during the next quarter.

REPORTS OF TECHNICAL PROGRESS-LABORATORY STUDIES

6. DEVELOPMENT OF GRAPHITE SOURCE

a. Background

In order to provide a high-irradiance, large-area thermal radiation source for edge-effect and source-geometry studies, a 150-kw graphite-lined, graphite-resistor furnace was built for the Naval Material Laboratory. The chamber has a 1-ft-square aperture and is 7 inches deep. The irradiance at the center of the aperture for each furnace temperature has been found to equal roughly black-body emittance at the same temperature; for the practical maximum of 2400°C, the irradiance at the center of the aperture is 70 cal/cm^{2}sec. The irradiance at 2 inches transversely from the center, drops to about 96 per cent of this value, and at 4 inches to about 65 per cent. A 10-inch circular-aperture shutter was constructed for this source; exposure times of 0.1 to 10 sec are possible.

b. Progress

No additional work was done, since sufficient data have been gathered to permit use of this source. Since field-test data indicate that the carbon-arc source gives valid results for the usual kind of flat sample, it appears that the major use of the wide-area source will concern special large assemblies. In this category lies the testing of field samples.

7. DEVELOPMENT OF ALUMINUM-SUN SOURCE

a. Background

The aluminum-sun source was developed, from its original form as a ceramic sphere in which aluminum was burned, by the Research Institute of Temple University under the technical direction of NML. The present model consists of a water-cooled, 14-in.-square steel box, 7 inches high. Within this box is welded a vertical, steel cylindrical container, 10 inches in diameter, lined with alumina. The lid of the box contains a 6-in. circular window to permit exposure of specimens. Advantages of this source, compared with other large-area sources, are its higher temperature (over 3000°C), its simple installation (only a 5 gpm water supply and room for a few tanks of oxygen), its low cost of construction and operation, and the fact that it can be used comfortably even in a small room. Its disadvantage is that its runs last only an hour, after which the solidified contents must be dumped. The method of fueling the source automatically has not as yet been thoroughly investigated.

b. Progress

High-speed motion pictures were taken of the action of the shutter built for this source in order to determine its time characteristic. A radiometer with 17 elements was fabricated to measure the spatial distribution, and readings were taken during several runs. The central irradiance is about 8 cal/cm^{2}sec at the beginning of a run, and rises gradually to about 22 cal/cm^{2}sec during the one-hour run. The irradiance drops to 85 per cent of its central value at 1 1/2 inches from the center and to 65 per cent at 3 inches. The effect of the rate of feeding oxygen on the irradiance and the spectral distribution will be investigated.

8. CRITICAL THERMAL ENERGIES OF SERVICE MATERIALS

a. Background

The purpose of this investigation is to evaluate the thermal radiation characteristics of the materials which are of special interest to the Armed Forces. The critical energy values of the various materials are being determined experimentally and reported as significant data become available. In addition, changes of critical energy values under the influence of individual parameters of the materials are evaluated and the effects on material assemblies are being determined.

b. Progress

The personnel and equipment normally employed in the Services Testing Program have been utilized for laboratory calibrations in connection with the participation of the Wright Air Development Center, Naval Air Material Center and the Strategic Air Command in Operation UPSHOT-KNOTHOLE.

In order to study the effects of flame-retardant treatments on fabrics, the critical thermal energies of three rayon fabrics were determined. One fabric was untreated, the second fabric was treated with a metallized coating and the third was treated with Pyroset and metallized. It was found that neither the metallizing process nor the Pyroset treatment in combination with metallizing increases the resistance of the basic fabric to thermal radiation. The critical energy corresponding to destruction of the untreated fabric is 9.6 cal/cm^2 and that of the treated fabrics is 6.4 to 7.1 cal/cm^2. At lower radiant exposures, the apparent transmittance of the aluminized fabric is less than that of the non-aluminized fabric.

The critical thermal energies and apparent transmittance of thermal radiation of specially treated, plasticized and aluminized awning materials were determined for the Bureau of Ships. In general, the plasticized materials showed a higher resistance to thermal radiation than the aluminized materials. In addition, the apparent transmittances determined from the effects on the carbon paper indicator ranged from 1.35 to 4.8 per cent on the plasticized materials and from 1.3 to 5.2 per cent on the aluminized materials. Silicon rubber on glass combines a very high critical thermal energy (88 cal/cm^2) with low apparent transmittance (1.35 per cent).

Another study of the effectiveness of the aluminizing process on fabrics involved cotton and asbestos fabrics submitted by the Minnesota Mining and Manufacturing Company, St. Paul, Minnesota. It was found that the metallizing process reduces the optical transmittance of the fabrics to a negligible value. However, the critical energy values of cotton materials were lowered if the metallizing process was used, while those of asbestos materials were increased. The difference in effect of the metallizing process on the cotton and asbestos fabrics is probably due to the differences in the melting and ignition points of the base fabrics. The apparent thermal-radiation transmittance of metallized fabrics is, in general, lower than that of the non-metallized fabric.

9. DEVELOPMENT OF PROTECTIVE MEASURES

a. Background

The objective of this program is to evaluate the resistance to thermal radiation of various types of building and textile materials which have been coated or impregnated with the most effective commercial fire-retardants. An attempt will be made to correlate the results of field and laboratory exposures, so that further evaluations of protective measures can be accomplished by means of a laboratory source. The results of these studies will indicate the direction of further developmental work on the commercial products to obtain the maximum thermal protection of materials. A survey of the commercial products of various manufacturers has been completed. Samples of surface coatings, building materials, impregnating compounds for fabrics and treated cloths have been obtained. A quantitative laboratory method of evaluation of the relative efficiencies of the water-soluble type flame-retardants has been developed and employed in the initial study of these compounds.

b. Progress

Depth-of-char studies on the coated woods exposed at Operation BUSTER have been completed and the report is being processed.

Using No. 29 Whatman Black Filter Paper strips as base material, critical energy values and weight loss have been determined as a function of energy density for ten samples of flame-retarding impregnating compounds for various add-ons ranging from 5 to 25 per cent. The compounds have been classified according to their predominant chemical constituents and grouped according to their relative standing as effective agents for increasing the resistance of cellulose-like materials to short-duration, high-intensity thermal radiation. These data are summarized in Enclosures (1) and (2). These data apply to a single-layer, air-background system. Multiple layers in which the outer one is flame-retarded have not been considered as yet, but will be investigated later as the skin-simulant program develops.

To study the effect of color of the base material, white and gray filter papers will be employed in some evaluation studies. Studies of commercial fire-retarding paints in two, three and four layer systems on white pine will continue.

On the basis of the flame-retardant studies the following conclusions may be drawn. All of the flame retardants evaluated increased the flame and glow resistance of the black paper. The critical energies to cause burn-through of the paper were higher for the flame-retarded specimens for all add-ons. The critical energies to cause char-through were in some cases lower and in others higher then those for untreated specimens, indicating the directing tendency of the flame retardant to promote earlier char formation. There appears to be some correlation between the critical energy to cause burn-through, and the chemical type of the compounds. The phosphates have somewhat higher critical energy values than the sulfamates and borates.

10. EFFECTS OF SOURCE SPECTRUM ON THERMAL DAMAGE TO MATERIALS

This problem has been inactive for some time due to the higher priority of other problems. A summary of the findings to date is being prepared. In general, the damage to a material caused by a source of a given spectral energy distribution correlates well with the total absorptance of the material for that source. Since the absorptance of most materials is greater for the shorter wavelengths, a source with significant radiation in the shorter wavelengths, will cause significant damage.

11. RECIPROCITY STUDIES

a. Background

The purpose of the reciprocity studies is to determine the effect of the rate of application of radiation (irradiance) on the degree of damage to materials caused by the radiation. In addition to the investigation of the range of irradiances where reciprocity holds, that is, wherein the same incident energy per unit area (radiant exposure) causes the same damage regardless of the rate of application of energy, of considerable importance is the determination of the irradiance-damage relationship for the range of irradiances in which reciprocity does not hold.

The study of reciprocity is essential in order to extrapolate critical energy data obtained at one rate of application of energy to others, such as those occurring in the field.

The methods and equipment employed in this study were described in the September, 1951 Quarterly Progress Report. The experimental results on maple wood, tropical-weight wool and clear Bakelite are described and discussed in the December, 1951 Quarterly Progress Report. The contribution of the "tail" of the thermal radiation pulse of a bomb detonation in furthering damage was made and reported in the June, 1952 Quarterly Progress Report.

The contribution of the tail of a pulse in producing further damage on 9 oz/yd^2 cotton sateen, 06107, has been investigated. During this experiment the irradiance in the second half of a 1-sec exposure was adjusted to be a desired proportion of the irradiance in the first half of the exposure. The initial and final irradiances were varied until the cotton sateen was charred through for the 1-sec pulse. The cloth sample was held stationary with an air background. The data indicate that for "tail" energies which are 15 to 35 per cent of the energy in the basic pulse, the "tail" does contribute significantly to the total damage to the cloth; the energy in the "step" pulse required for destruction is substantially the same as the energy in a square-wave pulse producing the same degree of damage.

Methods of duplicating the shape of the field pulse were investigated. An ordinary screen door check was mounted with its piston rod attached to the operating handle of the radial shutter of the searchlight housing in which the source is installed When the shutter begins to close, it works against the doorcheck. The manner in which this check retards the closing of the shutter may be regulated by adjusting the amount of air that is trapped by the piston on its down stroke. To determine the shape of a pulse delivered by this arrangement, a photoelectric cell was mounted at the focus of the receiver and irradiated; the intensity-time trace was recorded by a General Electric recording oscillograph. The shape of the pulse, which is shown in Enclosure (3), compares favorably with the shape of the intensity-time curves obtained in the field. The opening time of the shutter was controlled by a variable resistance in its operating circuit.

12. REFLECTOMETRY

a. Background

The purpose of this investigation is to study the reflectance and transmittance of materials, including dependence on wavelength, angle of incidence of the radiation, and previously sustained damage. The spectral reflectance and transmittance of various materials of interest in the investigation of damage by thermal radiation were measured; the radiant absorptances of these materials were calculated for sources of interest. These results have been published in various reports covering the complete investigations of the thermal properties of the materials and also in previous quarterly progress reports. The instruments and techniques employed in the investigation of reflectance and transmittance have been continuously improved to make possible more accurate measurements on the different types of materials involved.

b. Progress

The transmittance values for cloths measured with a PbS cell directly behind the cloth, in general, were higher than those determined from measurements with the General Electric Recording Spectrophotometer. The discrepancy between the two sets of data and the desire to resolve it have caused the summary report on the reflectance and transmittance of materials to be delayed. The new measurements based on the General Electric Recording Spectrophotometer data correlate well with the Sphere Reflectometer measurements.

13. THERMAL AND OPTICAL CHARACTERISTICS OF ENIWETOK SAND

The report on the thermal and optical characteristics of Eniwetok sand has been completed and distributed to the AFSWP Thermal Radiation Distribution List. This problem, therefore, is considered closed.

14. EFFECT OF REFLECTION FROM SAND ON RADIANT EXPOSURES

The report on the "Reflection of ABD Thermal Radiation by a Diffusing Ground Surface" has been completed and distributed; this problem, therefore, is considered closed.

15. THERMAL CHARACTERISTICS OF UNIFORM CLOTHING

a. Background

The objective of this problem is to study the heat transfer through one or more layers of uniform clothing under exposure to high-intensity thermal radiation; to determine the effects of physical parameters, including weight, weave, color, lamination, etc., on the transfer of heat through clothing.

The thermal characteristics of clothing, particularly the radiant exposures required to produce certain destructive effects on the materials, have been studied as part of the Services Testing Program. The purpose of this investigation, however, is to determine the physical parameters of clothing influencing the burns caused by thermal radiation to personnel. The first phase of this study is the development of a good substitute for skin to allow physical measurement, either by active or passive indicators, of the heat transfer through clothing materials. The second phase is the correlation of the physical data with those of the actual burns produced on pig skin for identical exposure conditions. During the special investigation of heat-treated Orlon, the usefulness of measuring the temperature rise at the interface between cloth and backing was demonstrated. A meat backing was employed for the Orlon studies, but because of its inherent disadvantages it has been replaced by polyethylene. Theoretical calculations and experimental work have shown that the temperature-time relationship of polyethylene for a 0.5-second thermal pulse is almost identical with that of the meat used in the study of Orlon characteristics.

b. Progress

The black form of polyethylene was chosen to reduce its diathermancy and to decrease the amount of radiation directly absorbed by an imbedded thermocouple. The initial experimental work on the effect of thermocouple placement, thermocouple wire diameter, contact pressure, spacing between cloth and backing, and exposure time has been completed. It was difficult to reproduce thermocouple placement unless the couple was actually visible at the surface. A very small error in distance below the surface results in large temperature differences. The main considerations for surface temperature measurements, however, are that the threshold burn is a surface phenomenon and that indicators at any but very small depths would not delineate between a short high-temperature exposure which would produce a surface burn and a longer low-temperature exposure which would not result in a burn. Experiments with No. 30 and No. 40 thermocouple wire molded into the front surface of a black polyethylene block indicated that the thermocouple size does not influence the temperature rise.

The effect of cloth pressure and that of the spacing between cloth and backing is shown in Enclosure (4). The cloth pressure was computed as the tension divided by the product of the width and the radius of curvature of the backing. A cloth pressure of 25 g /cm^2 must be exceeded to eliminate the influence of cloth pressure. Very low cloth pressure or non-positive contact will give very erratic results, as evidenced by the jump to almost twice the temperature rise if one compares the data for a cloth with almost no spacing with those for one with very light pressure against the backing. The decrease in maximum temperature rise as the spacing is increased, suggests that either the area of exposure was inadequate or that the heat transfer mechanism is complex, involving both radiation and convection. The distribution of irradiance over the exposure area for the ellipsoidal mirror and the 11-mm. carbon arc was 21.1 cal/cm^{2}sec for the central 5 mm , 14.8 cal/cm^{2}sec over the annulus defined by diameters of 5 and 9 mm , and 14.5 cal/cm^{2}sec over the annulus defined by diameters of 9 and 19 mm. The maximum temperature rises of the surface of the skin simulant using apertures in front of a single cloth in good contact determined experimentally, indicated that the energy outside the 9-mm spot does not affect the maximum temperature rise. A similar experiment using a spacing of 2 mm shows the inadequacy of the area exposed to radiation to simulate the infinite-area-exposure condition in which the temperature rise would be independent of spacing.

The effect of rate of application of energy on maximum temperature rise is shown in Enclosure (5). For a single layer of cotton sateen in contact or with 2 mm. spacing, there is no significant difference in maximum temperature rise for radiant exposures up to 10 cal/cm^2 for irradiances between 5 and 20 $cal/cm^2 sec$. For 10 cal/cm^2 the temperature rise was lower than that which would be predicted by extrapolation from lower radiant exposures. Because of the higher cloth temperatures involved, this is probably caused by greater reradiation and convection losses from the front surface of the cloth. Energy may be required to char the front face of the cloth and this energy is not transferred to the backing; this charring is initiated at approximately 7 cal/cm^2. On the other hand, the charred cloth has an absorptance of 0.87 compared with an initial absorptance of 0.77, indicating an increase in absorptance of approximately 13 per cent. The total diffuse transmittance is decreased by charring from 0.015 to less than 0.005. Changes in the thermal properties of the cloth may also be involved. For radiant exposures greater than 10 cal/cm^2 the burning or glowing of the cloth modifies the temperature-time-radiant exposure relationship, especially for the spacing condition for which the backing does not influence the temperature of the cloth. When exothermic reactions occur in the cloth, it is physically distorted and either more energy is transmitted to the backing if the cloth remains in contact with the backing or, if the cloth is distorted away from the backing, less energy is transmitted to the backing. A temperature rise often results which is considerably lower than that obtained at a lower radiant exposure at which the cloth is not affected.

To determine the effect of high ambient humidity on the protection of fabrics the standard cloth was subjected to 100 per cent relative humidity at 4°C for 24 hours, resulting in a 3 per cent increase in mass. It was then exposed in contact with the skin simulant to a radiant exposure of 10 cal/cm^2 delivered in 0.5 seconds. The temperature rise was 2 per cent lower than that of the control sample, which is well within the present error of reproducibility of ±5 per cent.

Enclosure (6) presents the temperature history curves for 1,2, and 4 layers of the standard cloth for both contact and spacing. Evident are the longer times for the maximum temperature rises with multilayers or thicker assemblies than for the single layer condition. The initial temperature rise for the single cloth when spaced away from the backing probably results from the transmission of the carbon-arc radiation through the single cloth to the backing.

Temperature-time relationships have been derived from theoretical considerations for several conditions of importance. For a single opaque medium of semi-infinite thickness the expression for the temperature rise of the irradiated face is

$$\theta = \frac{2AH}{\sqrt{\pi K \rho c}} \left(t^{1/2}\right) \qquad (1)$$

For an opaque medium of finite thickness the temperature of the irradiated face is:

$$\theta = \frac{2AH \, t^{1/2}}{\sqrt{\pi K \rho c}} \left[1 + 2\sum_{n=1}^{n=\infty} e^{-(2nZ)^2} - \sqrt{\pi} \;\; 2nZ \; \mathrm{erfc}(2nZ) \right] \qquad (2)$$

For an opaque medium of finite thickness in contact with an opaque medium of semi-infinite thickness, the temperature of the interface is:

$$\theta = \frac{4AH\, t^{1/2}}{\sqrt{\pi K \rho c}} \frac{1}{1+\sigma} \sum_{n=0}^{n=\infty} \alpha^n \left[e^{-(2n+1)^2 Z^2} - \sqrt{\pi}\,(2n+1)Z \,\mathrm{erfc}(2n+1)Z \right] \tag{3}$$

For a diathermous medium of finite thickness in contact with a diathermous medium of semi-infinite thickness, the temperature of the interface is:

$$\theta = \frac{AH}{1+\sigma} \Bigg\{ e^{-r_1 l} \Bigg\langle \frac{1}{K_1} \Bigg\{ 2\left(\frac{\kappa_1 t}{\pi}\right)^{1/2} + \frac{e^{\kappa_1 r_1^2 t}\,\mathrm{erfc}(r_1\sqrt{\kappa_1 t})}{r_1} - \frac{1}{r_1} \tag{4}$$

$$+2\sum_{n=0}^{\infty} \alpha^n \Bigg[-2\left(\frac{\kappa_1 t}{\pi}\right)^{1/2} e^{-(2nl)^2/4\kappa_1 t} + 2nl\,\mathrm{erfc}\left(\frac{2nl}{2\sqrt{\kappa_1 t}}\right)$$

$$+ \frac{1}{2r_1} e^{\kappa_1 r_1^2 t} \Bigg\langle e^{-2nlr_1}\,\mathrm{erfc}\left(\frac{2nl}{2\sqrt{\kappa_1 t}} - r_1\sqrt{\kappa_1 t}\right) - e^{2nlr_1}\,\mathrm{erfc}\left(\frac{2nl}{2\sqrt{\kappa_1 t}}\right.$$

$$\left. + r_1\sqrt{\kappa_1 t}\right) \Bigg\rangle \Bigg] \Bigg\}$$

$$\frac{+\sigma}{K_2} \Bigg\{ 2\left(\frac{\kappa_2 t}{\pi}\right)^{1/2} \frac{e^{\kappa_2 r_2^2 t}}{r_2}\,\mathrm{erfc}\,(r_2\sqrt{\kappa_2 t}) - \frac{1}{r_2}$$

$$-2\sum_{n=1}^{\infty} \alpha^n \Bigg[-2\left(\frac{\kappa_1 t}{\pi}\right)^{1/2} e^{-(2nl')^2/4\kappa_2 t} + 2nl'\,\mathrm{erfc}\left(\frac{2nl'}{2\sqrt{\kappa_2 t}}\right)$$

$$+ \frac{1}{2r_2} e^{\kappa_2 r^2 t} \Bigg\langle e^{-2nl' r_2}\,\mathrm{erfc}\left(\frac{2n'}{2\sqrt{\kappa_2 t}} - r_2\sqrt{\kappa_2 t}\right) - e^{2nl' r_2}\,\mathrm{erfc}\left(\frac{2nl'}{2\sqrt{\kappa_2 t}} - r_2\sqrt{\kappa_2 t}\right) \Bigg\rangle \Bigg] \Bigg\} \Bigg\}$$

$$+2\sum_{n=0}^{\infty} \alpha^n \left[2\left(\frac{\kappa_1 t}{\pi}\right)^{1/2} e^{-[(2n+1)l]^2/4\kappa_1 t} - (2n+1)\,\mathrm{erfc}\left(\frac{(2n+1)\,l}{2\sqrt{\kappa_1 t}}\right)\right.$$

$$-\frac{1}{2r_1}\, e^{\kappa_1 r_1^2 t}\Big\langle e^{-(2n+1)\,l r_1}\,\mathrm{erfc}\left(\frac{(2n+1)\,l}{2\sqrt{\kappa_1 t}} \quad r_1\sqrt{\kappa_1 t}\right)$$

$$\left.\left. -e^{(2n+1)\,l r_1}\,\mathrm{erfc}\left(\frac{(2n+1)\,l}{2\sqrt{\kappa_1 t}} + r_1\sqrt{\kappa_1 t}\right)\Big\rangle\right]\right\rangle\Big\}$$

$$l' = l\sqrt{\frac{\kappa_2}{\kappa_1}}.$$

In these relationships,
H is the irradiance in cal/cm^{2}sec
A is the absorptance
t is the time in seconds
K is the conductivity
ρ is the density
c is the specific heat
l is the thickness of the finite medium

$$\sigma = \sqrt{\frac{K_2\rho_2 c_2}{K_1\rho_1 c_1}}$$

$$\alpha = \frac{1-\sigma}{1+\sigma}$$

$$\kappa = \frac{K}{\rho c}$$

$$Z = \frac{l}{2\sqrt{\kappa t}} = \frac{l\,\rho c}{2\sqrt{Kt}}$$

$$\mathrm{erfc}\; y = 1-\frac{2}{\sqrt{\pi}}\int_0^y e^{-x^2}\, dx$$

The effects of reradiation and convection losses have not been included in the derivations. The heat transfer mechanism, which is a combination of direct optical transmission, convection of hot air and distillation products, and reradiation, has not yet been analyzed.

The above equations assume that the irradiance, H, remains constant during the time interval of interest. If H varies, a solution for the temperature may be found by considering the time interval broken into sub-intervals in each of which H remains constant. The expression for the temperature during any one of these sub-intervals is then equal to the algebraic sum of the sequence formed as follows: corresponding to the beginning point of each sub-interval, from the first up to and including the sub-interval being considered, a term of the sequence is formed by substituting in the appropriate expression for θ above, the increment in H for H, and $t-t_n$ for t, where t_n is the time at the beginning of the n^{th} sub-interval. Enclosure (7) shows graphically the results of such a calculation for the case of Equation (1) for a typical laboratory constant-irradiance pulse of 0.5 sec, and for a simulated field pulse, of equal radiant exposure, consisting of a 0.3-sec constant-irradiance pulse followed immediately by a 0.6-sec pulse of 80 per cent lower irradiance. It is to be noted that the temperature rise for the "field pulse" is but 91 per cent of that for the square-wave pulse. The temperature-time history is such that the maximum temperature rise would not be affected greatly by energy received after the peak of a field pulse. It would appear that for a material whose damage criterion is one of maximum temperature, only 50 to 80 per cent of the energy of a field pulse is effective.

The constants of interest in these studies are as follows:

	Cotton Sateen 9oz/yd^2, CC107	Black Polyethylene	Human Skin
Conductivity (C.G.S. Units)	6.1×10^{-5}	8×10^{-4}	10×10^{-4}
Density (g/cm^3)	0.70	0.92	1.0
Specific heat	0.35	0.55	1.0
Carbon-arc Absorptance	0.77	0.95	0.70
Carbon-arc Transmittance	0.015	--	--
Thickness	0.043	--	--

The thermal constants for cotton and human skin are derived from the best available data. The absorptance and transmittance values were determined with the NML Sphere Reflectometer.

From Enclosure (7.) the maximum temperature rise per cal/cm^2 for a 0.5-sec rectangular pulse is 320°C for the cotton sateen, 76°C for black polyethylene and 36°C for human skin. A tentative value of 50°C per cal/cm^2 for black polyethylene has been obtained by NML and a tentative value of 27°C per cal/cm^2 for pig skin has been obtained by the University of Rochester Medical School. The expression for the single medium suggests that either the absorptance or $K\rho c$ of one substance may be altered to simulate exactly the temperature-time curve of another substance. Thus, an absorptance of 0.44 for polyethylene would give it the temperature-time curve of the human skin with the constants given.

For cotton sateen Equations (1) and (2) give the same initial temperature history for a 0.5 sec irradiance, the difference between the two relationships becoming apparent after 1 sec.

The maximum temperature rise for the front face of the cotton sateen, for the constants as given, is very high and indicates the probable importance of the effects of reradiation. The temperature-time curve for the double-opaque -medium condition with a single layer of cotton sateen and black polyethylene as computed from Equation (3) is given in Enclosure (8). The shape of the curve compares favorably with the experimental curve of Enclosure (6). The maximum temperature is about 60 per cent too high, probably because of neglect of reradiation and convection losses. The fact that the temperature peak of the cloth-backing interface occurs at an appreciable time after the irradiance has dropped to zero indicates that the actual pulse shape in the field should not give a temperature history significantly different than the square-wave laboratory pulse.

The work during the next Quarter will be concerned with preparations for the field test.

16. EFFECT OF THERMAL RADIATION ON MECHANICAL PROPERTIES OF AIRCRAFT ALLOYS

a. Background

The Wright Air Development Center is studying the effect of thermal radiation on the mechanical strength of aircraft structure members. The WADC requested NML to expose specimens to the laboratory source and the Center would measure the mechanical characteristics before and after exposure.

b. Progress

The exposures have been started and should be completed on or before 1 February. An apparatus was constructed to hold the sample under tension while irradiated. The specimen is suspended in a horizontal position between the vertical supports of a box-like channel iron frame. Tension is applied by taking up on a 1-inch bolt mounted through a hole in one of the supports and attached to the sample. A dynamometer, placed between the sample and the bolt indicates the stress on the sample. The temperature rise of the sample is measured with thermocouples.

17. CALORIMETRY

a. Background

The purpose of this investigation is to develop the high-irradiance radiometers required by NML in its thermal program, and to calibrate these and radiometers submitted by other agencies.

b. Progress

In its laboratory program NML uses a relatively heavy (100-200 grams), copper cavity that is cone-shaped as a standard for high intensity radiant flux measurements. An accurately timed shutter is used for exposures, and thermocouples and a sensitive galvanometer are used to measure the temperature rise. The handbook value of the specific heat of copper is used to compute the radiant exposure. Suitably blackened copper buttons of small mass (1-5 gms), have been found to give similar results to the heavier cavity and are used for routine check measurements. A radiometer consisting of a single, directly exposed, thin wire thermocouple was calibrated for the University of Rhode Island. The sensitivity was 1.5 cal/cm^{2}sec per millivolt with a time constant of 0.12 seconds. The radiometer was sensitive to air currents and must be covered for accurate use. The two heavy copper cylinder calorimeters submitted by the Army Chemical Center were deemed too heavy for practical use and were not calibrated. Another radiometer was subsequently received from the Army Chemical Center and was calibrated. This radiometer consisted of a nickel slug with 8 thermojunctions and a nickel alloy thermal compensating bridge. The sensitivity was 2.43 millivolts per cal/cm^2. The time constant was about 30 seconds. The radiometer was of limited application for field and laboratory problems in high intensity radiation.

A radiometer was constructed for measuring the spatial distribution of irradiance of the aluminum-sun source. The radiometer consists essentially of 17 cylindrical copper bodies which are embedded with ends flush in a slitted copper plate which acts as a guard ring.

A copper button type calorimeter suitable for laboratory or field use has been designed and is being constructed.

REPORTS SUBMITTED

The progress of the Naval Material Laboratory in its Thermal Radiation studies is summarized in reports which are prepared and distributed as significant findings warrant. To date, the following reports have been issued. Copies are available to the various activities on the Armed Forces Special Weapons Project Thermal Radiation Distribution List upon request. The reports released during the current quarter are indicated by an asterisk (*).

a. <u>Sources of Thermal Radiation and Methods of Exposure</u>

Report of Investigation of Gas-fired Radiant Panel Manufactured by Selas Corporation of America as a Source of Radiant Energy (Naval Material Laboratory Project 5046-2, Part 1, Unclassified) (March, 1951).

Report of Investigation of Analytical and Graphical Determinations of Cam Shapes for Imparting Specified Motions by Means of a Cord over a Fixed Pulley (NML Project 5046, Part 6, Unclassified) (January, 1950).

Determination of the Energy of High-Intensity Radiation at the Focus of a Parabolic Reflector, Using (A) a Black-body Receiving Cell; (B) Metal Foil Receiving Strips (NML Project 5046, Part 4, Unclassified) (July, 1949).

Determination of Intensity Distribution at the Focus of a Parabolic Mirror and the Energy Density on a Moving Surface Using a Tungsten Lamp Source (NML Project 5046, Part 5, Unclassified) (July, 1949).

Theoretical Requirements for a Laboratory Source of Thermal Radiation (NML Project 5046-3, Part 17, Restricted) (April, 1952)

b. Calorimetry

A Method of Measuring High Intensities at the Focus of a Parabolic Reflector with Large Relative Aperture (NML Project 5046, Part 3, Unclassified) (November, 1948).

c. Material Studies

The Critical Energies of the Materials Employed in the Material Laboratory Greenhouse Studies (NML Project 5046-3, Part 1, Confidential) (May, 1951).

The Critical Thermal Energies of Clothing Materials Submitted by the U. S. Marine Corps (NML Project 5046-3, Part 3, Confidential) (July, 1951).

The Critical Thermal Energies of Clothing Materials Submitted by Air Materiel Command, USAF (NML Project 5046-3, Part 4, Confidential) (August, 1951).

Thermal Radiation Characteristics of Orlon (NML Project 5046-3, Part 5, Confidential) (September, 1951).

Critical Thermal Energies of Cloths Submitted by Quartermaster General, U. S. Army (NML Project 5046-3, Part 6, Confidential) (March, 1952).

Critical Thermal Energies of Clothing Materials Submitted by Surgeon General, U. S. Army (NML Project 5046-3, Part 8, Confidential) (October, 1951).

Critical Thermal Energies of Clothing Materials Submitted by Bureau of Supplies and Accounts (NML Project 5046-3, Part 9, Confidential) (October, 1951).

Influence of Weathering on Critical Thermal Energies of Material Surfaces (NML Project 5046-3, Part 10, Confidential) (October, 1951).

Critical Thermal Energies of Paint-on-Metal Systems Submitted by the Bureau of Aeronautics, U. S. Navy (NML Project 5046-3, Part 15, Confidential) (March, 1952)

Critical Thermal Energies of Paint Systems Submitted by the Bureau of Ships, U. S. Navy (NML Project 5046-3, Part 16, Confidential) (April, 1952).

Critical Thermal Energies of Plastic Window Materials Submitted by the Air Materiel Command, USAF (NML Project 5046-3, Part 18, Confidential) (May, 1952).

Relative Protection Against Radiation Burns by Heat-Treated Orlon (NML Project 5046-3, Part 20, Confidential) (August, 1952).

Critical Thermal Energies of Plastic Materials Submitted by the Bureau of Ships (NML Project 5046-3, Part 22, Confidential) (August, 1952).

Critical Thermal Energies of Doped Fabrics and Additional Paint Systems Submitted by the Bureau of Aeronautics, Department of the Navy (NML Project 5046-3, Part 23, Confidential) (September, 1952).

Critical Thermal Energies of Special Fabric Materials Submitted by the Forest Products Laboratory, U. S. Forest Service (NML Project 5046-3, Part 24, Confidential) (September, 1952).

*Critical Thermal Energies of Aluminized Asbestos Cloths Submitted by the Wright Air Development Center (NML Project 5046-3, Part 26, Confidential) (December, 1952).

*Critical Thermal Energies of Packaging Materials Submitted by the Bureau of Supplies and Accounts, Department of the Navy (NML Project 5046-3, Part 25, Confidential) (December, 1952).

d. Reflectometry

A Reflectometer for Measuring Diffuse Reflectance in the Infrared Region (NML Project 5046, Part 9, Unclassified) (September, 1950).

Transmitting and Reflecting Characteristics of Inert Materials (NML Project 5046, Part 10, Unclassified) (March, 1951).

Reflectance and Transmittance of Forest Materials (NML Project 5046-3, Part 7, Unclassified) (April, 1952).

Reflectance and Transmittance of Thermal Source Components (NML Project 5046-3, Part 13, Unclassified) (April, 1952).

e. Effects of Atmosphere and Environment

The Spectral Characteristics of the Thermal Radiation of an Atomic Explosion (NML Project 5046-3, Part 2, Restricted) (May, 1951).

The Thermal and Optical Characteristics of Nevada Sand, (NML Project 5046-3, Part 19, Confidential) (June, 1952).

*Reflection of ABD Thermal Radiation by a Diffusing Ground Surface (NML Project 5046-3, Part 28, Confidential) (November, 1952).

*Thermal and Optical Characteristics of Eniwetok Sand (NML Project 5046-3, Part 29, Confidential) (November, 1952).

f. Protective Measures

A Survey of Measures for the Flame-proofing of Fabrics and Building Materials (NML Project 5046-3, Part 11, Restricted) (January, 1952).

Reduction of Thermal Radiation Damage by Means of Metallized Cloths (NML Project 5046-3, Part 14, Restricted) (March, 1952).

Value of Commercial Fire-retarding Treatments in Reducing Hazard from Flash Fires (NML Project 5046-3, Part 12, Confidential) (May, 1952).

Reduction of Thermal Radiation Damage by Means of Brompoly TAP and Aminophosphorus Resins (NML Project 5046-3, Part 21, Confidential) (May, 1952).

g. Field Tests

Thermal Radiation Measurements in Connection with Operation RANGER (NML Project 5046-7, Secret) (July, 1951).

Critical Energies of AFCRL Project 1.1 Materials (NML Project 5046-8, Part 1, Secret) (July, 1951).

Critical Energies of AFCRL Project 1.1 Materials (NML Project 5046-8, Part 2, Confidential) (August, 1951).

The Characteristic Behavior of Materials Attendant Upon Exposure to Thermal Radiation (GREENHOUSE Pre-Operation Report, Confidential) (December, 1950).

Summary Technical Report of Thermal Radiation Studies from 1947 to 1949 (NML Project 5046, Part 8, Confidential) (April, 1950).

Evaluation of Thermal Effects on Specimens Exposed at Bikini (NML Project 5046, Part 7, Confidential) (March, 1950).

Investigation of Radiation Effects on Wood Specimens Exposed During the Able Test at Bikini (NML Project 5046, Part 2, Restricted) (September, 1947).

Effect of Thermal Radiation on Materials, Operation BUSTER Project 2.4-2 (Report available through AFSWP) (NML Project 5046-8, Part 3, Secret).

Atmospheric Transmission and Weather Measurements, Operation TUMBLER-SNAPPER Project 8.4 (Report available through AFSWP) (NML Project 5046-10, Part 1, Restricted).

Measurements of Thermal Radiation, Using Passive Receivers, Operation TUMBLER-SNAPPER Project 8.3a (Report available through AFSWP) (NML Project 5046-10, Part 10, Part 2, Confidential).

Survey of Material Specimens Exposed at Able and Baker Tests and Submitted for Evaluation of Radiation Effects (NML Project 5046, Part 1, Restricted) (September, 1947).

*Apparatus and Methods for the Exposure of Materials to Thermal Radiation (NML Project 5046-1, Part 1, Restricted) (October, 1952).

h. Progress Reports

Bi-monthly Progress Report, NML Thermal Radiation Program, 1 December, 1950 (NML Projects 5046-2,-3, Confidential) (December, 1950).

Bi-monthly Progress Report, NML Thermal Radiation Program, 1 April, 1951 (NML Projects 5046-2,-3, Confidential) (April, 1951).

Thermal Radiation Studies, Report of Progress, July - September, 1951 (NML Projects 5046-2,-3, Confidential) (October, 1951).

Thermal Radiation Studies, Report of Progress, October - December 1951 (NML Projects 5046-2,-3, Confidential) (March, 1952).

Thermal Radiation Studies, Report of Progress, January - March, 1952 (NML Projects 5046-2,-3, Confidential) (April, 1952).

Thermal Radiation Studies, Report of Progress, April - June, 1952 (NML Projects 5046-2,-3, Confidential) (August, 1952)

*Thermal Radiation Studies, Report of Progress, July - September, 1952 (NML Projects 5046-2,-3, Confidential) (November, 1952).

Approved:

B. H. Andrews

B. H. ANDREWS, COMMANDER, USN
For the Director

CLASSIFICATION OF FIRE RETARDANTS

Group I - Flame and Glow Retardants

Class A - Phosphates	Manufacturer
1 - REZGARD A	Monsanto Chemical Co.
2 - FLAMEPROOF XWX-B	Apex Chemical Co.
3 - AKAUSTAN	General Dyestuff Corp.
4 - ALBI - "K"	Albi Mfg. Co., Inc.
5 - FLAMEPROOFING AGENT 313	Glyco Products Co., Inc.
Class B - Sulfamates	
1 - FLAMEPROOF #290-C	Apex Chemical Co.

Group II - Flame Retardants

Class A - Borates	
1 - QUAKER DIAPENE AB	Quakers Chemical Products Co.
2 - ARKO FLAMEPROOFING COMPOUND AS	Arkansas Co., Inc.
3 - ARKO FIRE RETARDANT 98 B	Arkansas Co., Inc.
4 - ABOPON	Glyco Products Co., Inc.

Group III - Non-Effectives

Class A - Chlorides

1 - Common Salt

CRITICAL ENERGIES AT BURN-THROUGH AND CHAR-THROUGH FOR DIFFERENT ADD-ONS

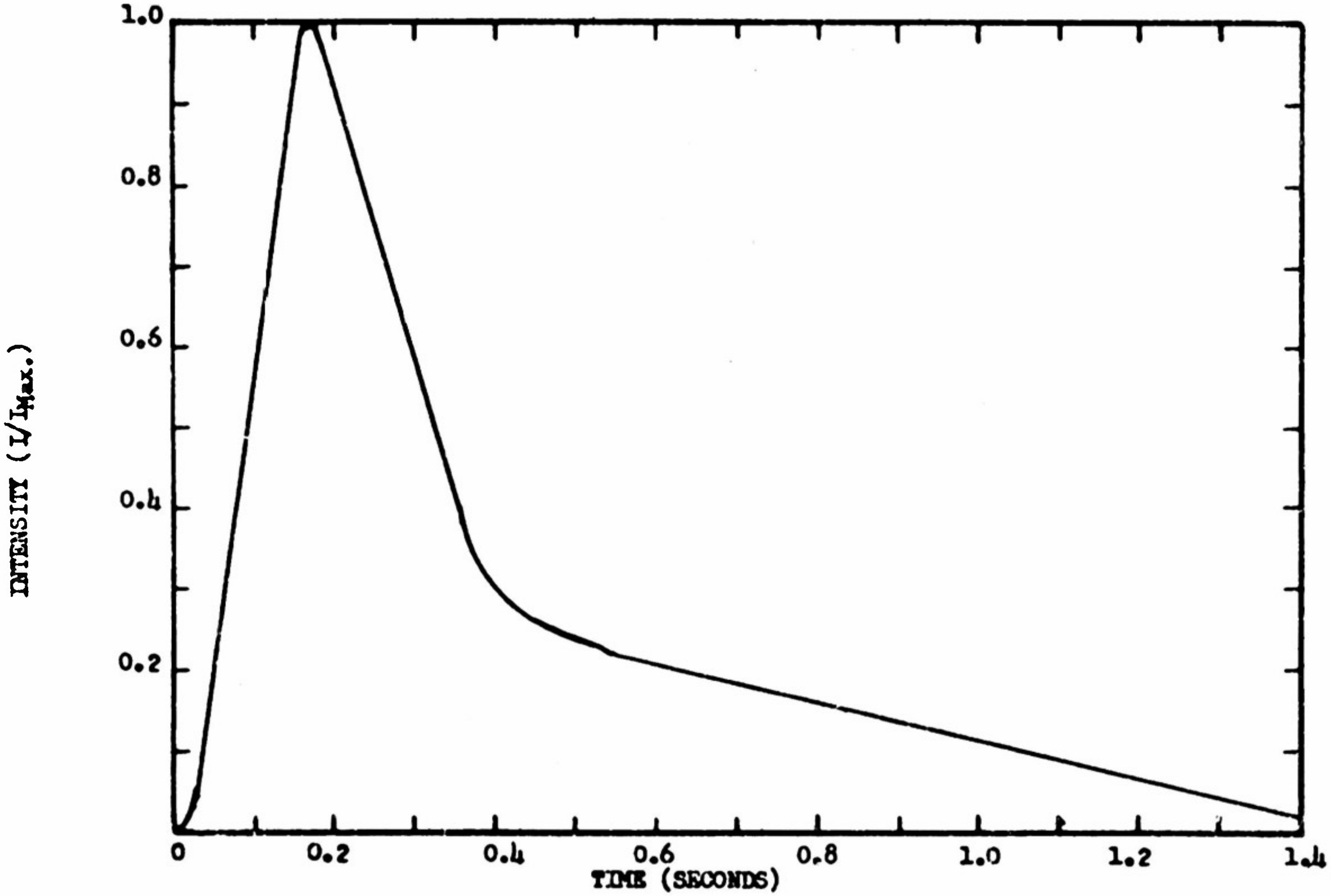
Trade Name	Burn-Through	Char-Through	Burn-Through	Char-Through	Burn-Through	Char-Through	Burn-Through	Char-Through	Burn-Through	Char-Through
	5 Per Cent		10 Per Cent		15 Per Cent		20 Per Cent		25 Per Cent	
REZGARD A	6.9	4.4	7.0	4.0	9.3	4.4	10+	4.1	10+	3.9
FLAMEPROOF XWX-B	7.4	4.1	6.9	4.5	7.3	4.4	6.5	3.7	6.4	3.7
AKALUSTAN	5.7	3.5	5.9	3.7	6.6	3.5	7.3	4.1	6.4	4.4
ALBI - "K"	6.4	4.4	6.4	3.7	6.6	4.4	6.9	4.4	6.8	3.7
FLAMEPROOFING AGENT 313	5.9	4.2	5.7	4.0	6.6	4.5	6.4	3.8	6.2	4.8
FLAMEPROOF #-290C	5.7	4.4	6.7	4.6	6.5	5.6	--	--	7.0	5.6
QUAKER DIAPENE AB	5.1	3.1	5.6	3.2	5.6	3.3	5.6	3.2	5.6	3.0
ARKO FLAME-PROOFING COMPOUND AS	5.6	4.1	5.6	3.7	5.6	4.4	5.3	4.0	5.4	4.2
ARKO FIRE RETARDANT 98 B	5.7	4.4	5.6	4.2	5.7	4.8	5.6	4.1	5.7	4.5
ABOPON	5.6	4.5	5.6	4.6	5.6	4.5	5.2	4.1	5.4	4.1
COMMON SALT	4.3	3.4	4.3	3.4	4.3	3.3	4.3	3.5	5.6	3.3

No. 29 Black Filter Paper: B-T = 4.5, C-T = 4.3

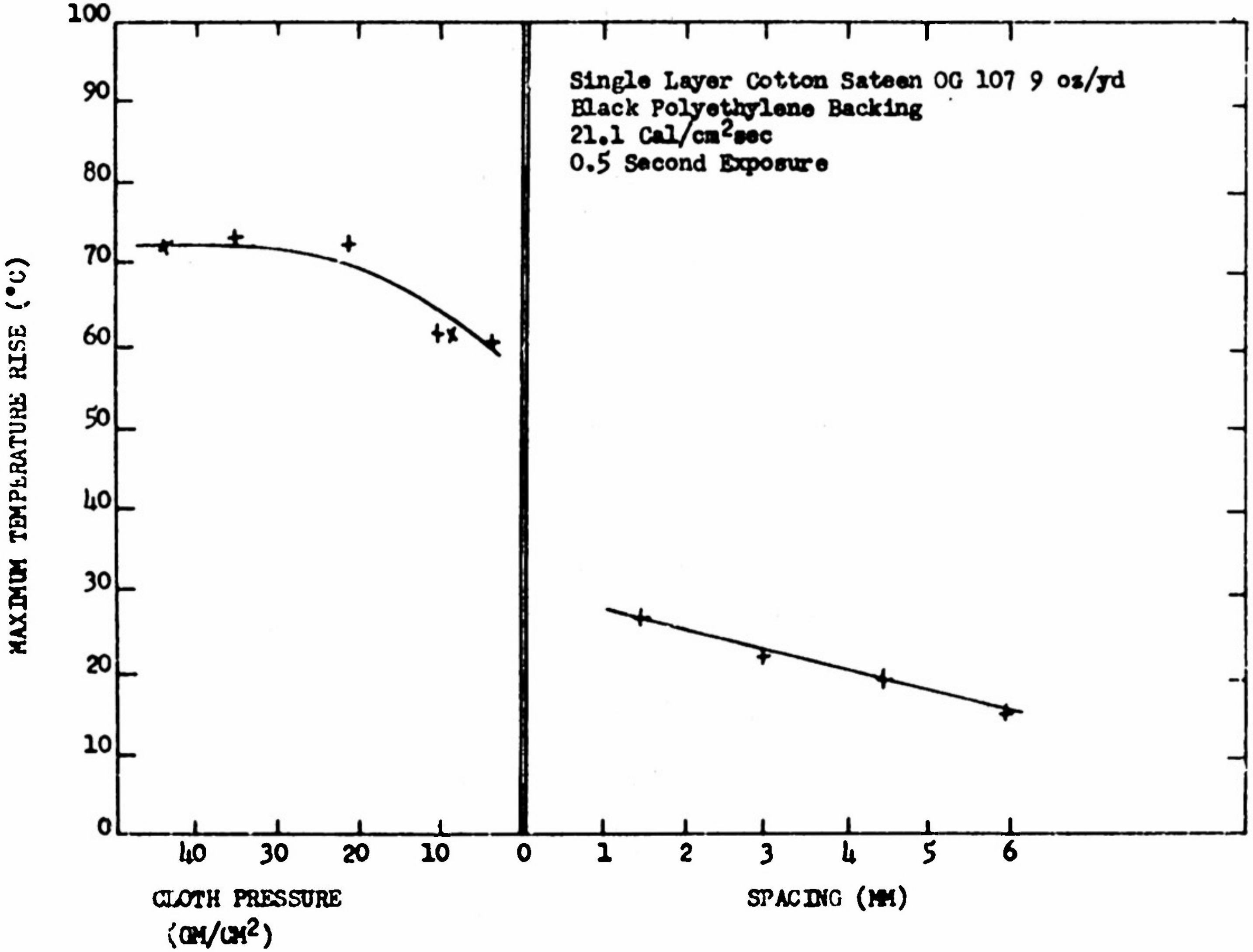
Notes: (1) Critical Energy (calories/cm^2): is the minimum or critical quantity of heat energy required to produce specific destructive effects.

(2) Burn-Through: That degree of destruction of material which results in the formation of a crack, hole or other opening.

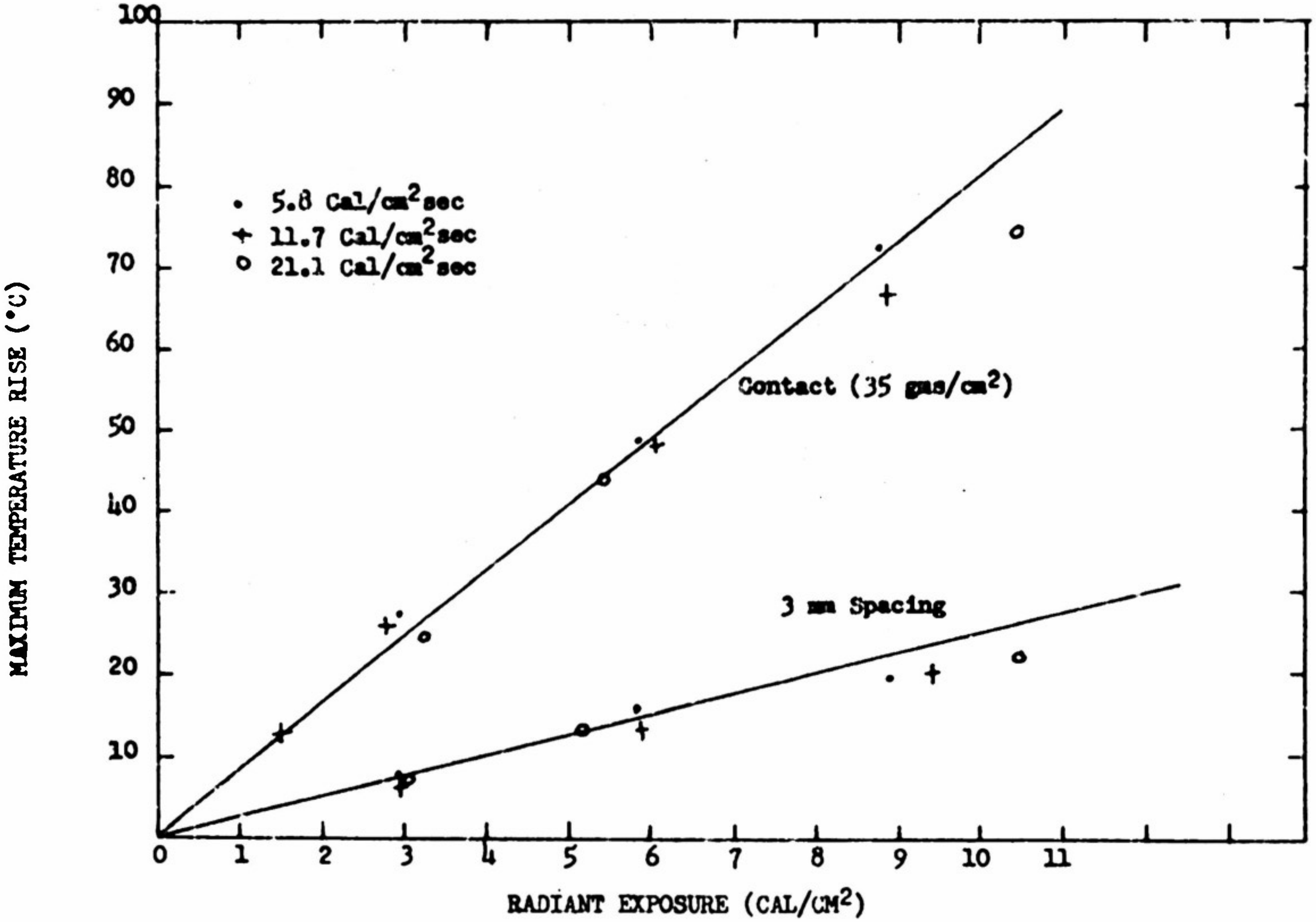
(3) Char-Through: That degree of destruction of material which results in the initial formation of char on the back or non-radiated surface.



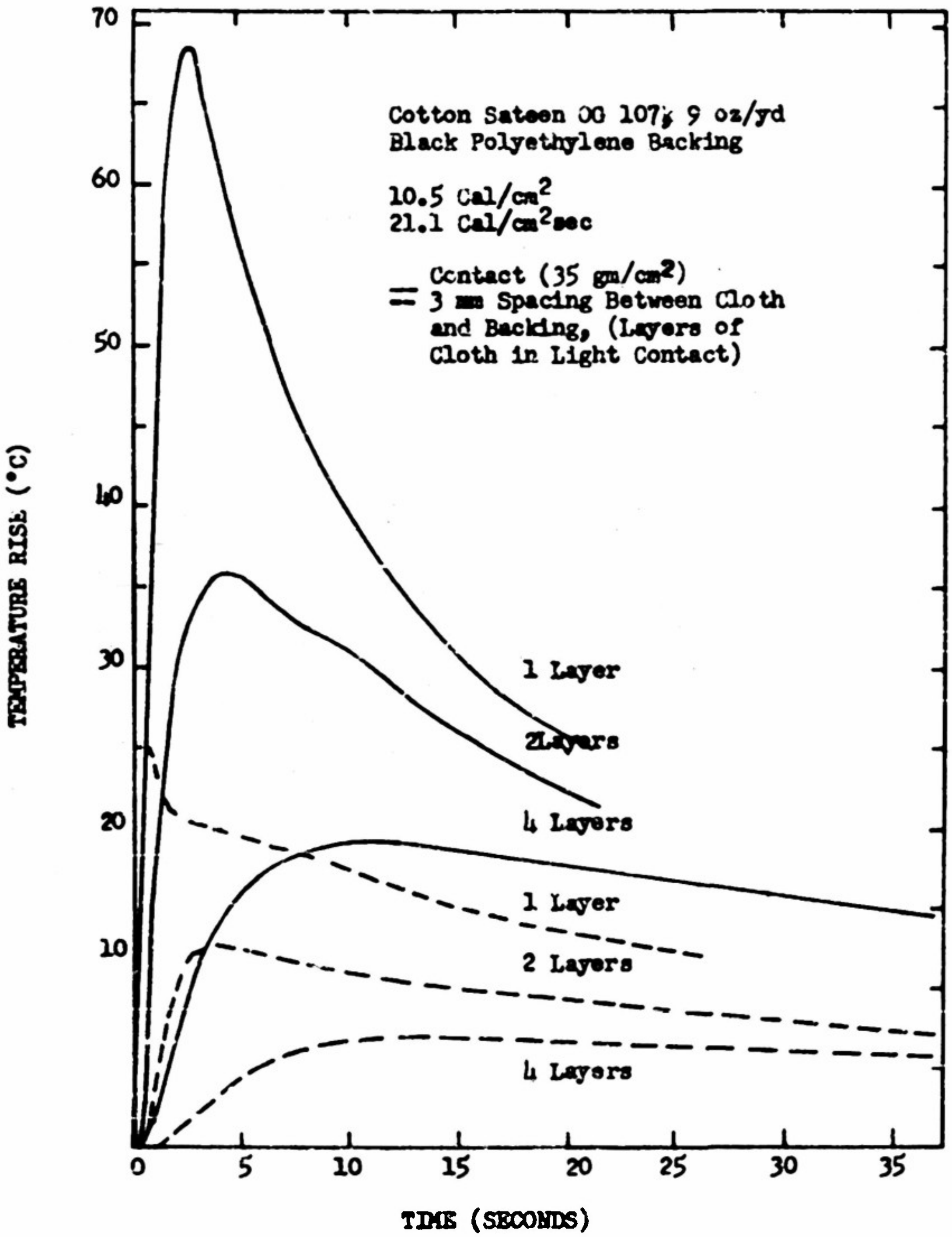
Typical Intensity-time Characteristic of Laboratory Source with Double Shutter



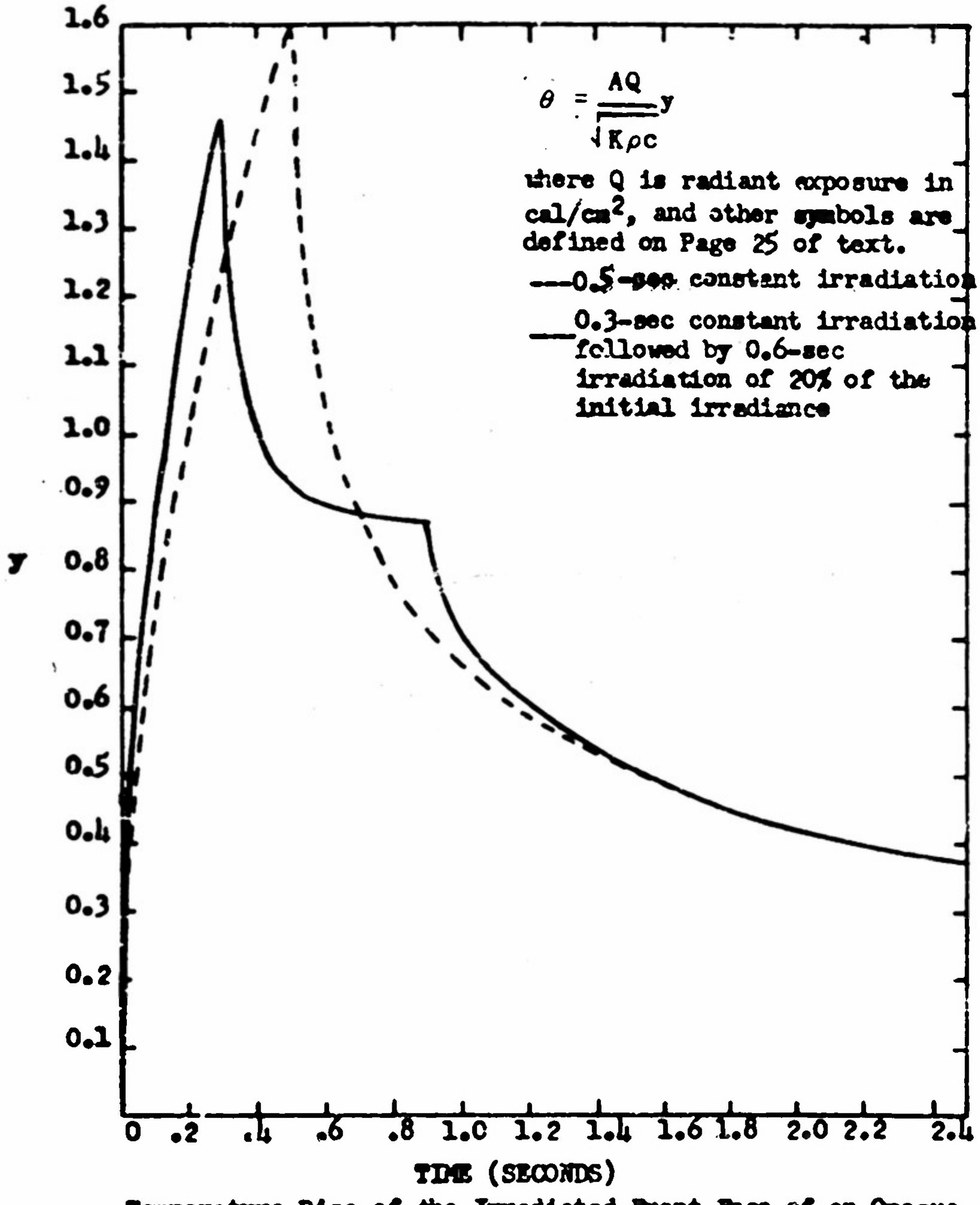
Effect of Pressure and Spacing on Temperature Rise



Maximum Temperature Rise as A Function of Radiant Exposure and Irradiance



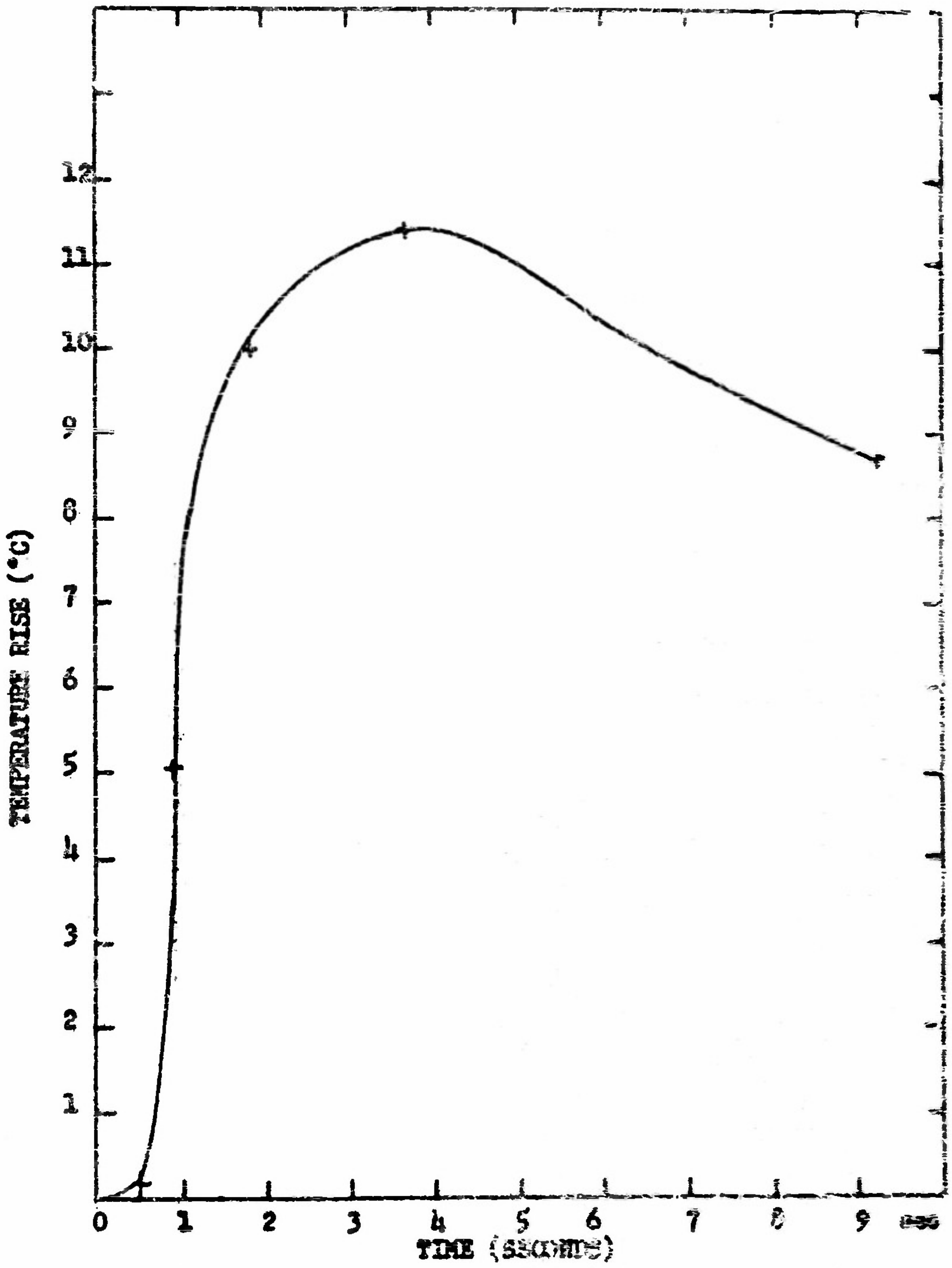
Temperature Rise for 1,2, and 4 Layers of Cloth in Contact and 3 mm Spacing



Temperature Rise of the Irradiated Front Face of an Opaque Semi-infinite Medium.

Lab. Projects 5046-2, 5046-3
Progress Report 8
Enclosure (8)

MATERIAL LABORATORY



Calculated Temperature Rise of Interface of Cotton Sateen, with Black Polyethylene Backing for Unity Radiant Exposure in 0.5 Second